Shortcurrent Testing Laboratories. Short-Circuit Performance of Power Transformers, Transformer Testing Experience

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Abstract

The electrodynamic testing of transformers consists in the creation in the process of the specific quantity of short-circuit shots (as a rule 5-6). In service winding electrodynamic deformations after short-circuit currents can result in insulation disruption and in to turn-to-turn internal short-circuit immediately.

All transformer design elements (Winding, pressing system, and etc.) must be checked during short-circuit testing by real values of short-circuit currents. Transformer testing for short-circuit withstand is an instrument for reliability improvement of power transformer design.

Keywords

Short-circuit; Testing Laboratory; Winding fault; Electrodynamic Deformation; Low Voltage Impulse Method

Introduction

Dozens tons of fire dangerous substances are inside the transformer tanks. If it starts burning due to winding failures, fire occurs, and further development of failure can move to the adjacent equipment, it will decrease reliability of electric power supply, increase financial damage from interruption of electric power supply and deteriorate ecological situation.

Failure rate depends on some factors. In service winding electrodynamic deformations after short-circuit currents can result in insulation disruption and further to turn-to-turn internal short-circuit immediately. However, in other cases, the insulation weakness center can probably appear in the winding deformation point. This insulation weakness center can exist in the winding for few years. And an increase of partial discharge (PD) intensity, which will result in insulation disruption is registered.

Power transformers are one of the basic parts in the circuitry of power transmission and delivery. Therefore the interest to perfection of the power transformers' fault diagnostic methods is increased. The repairs of power transformers and other electrical equipment are carried out, using diagnostic measurement results.

LVI-testing, FRA and short-circuit inductive reactance measurements are sensitive to detecting such typical transformers winding faults as buckling, axial shift and other. The 70 units of 25-240 MVA 110-500 kV power transformers have been checked by low voltage impulse (LVI) method. A few power transformers were detected with winding deformations after short-circuit with aperiodical short-circuit current.

Shortcurrent Testing Laboratories

FIG. 1 TOGLIATTY POWER TESTING LABORATORY, 1150 KV TEST STATION (RUSSIA)

22 units of power transformers extending in capacity range from about 25 MVA to over 666 MVA and in voltage range from 110 kV to 750 kV were tested at short-circuit at Togliatty Power Testing Laboratory, Russia, during 1983-1995 (fig. 1). The application of LVI method and measurement of inductive reactance deviation allowed detecting a twisting of low-voltage

winding and radial winding's deformations at tests of the 400MVA and a 250MVA block power transformers.

Transformer testing for short-circuit withstand is an instrument for reliability improvement of power transformer design. All transformer design elements (winding, pressing system, and etc.) must be checked during short-circuit testing by real values of short-circuit currents.

As known, the essence of the electrodynamic testing of transformers consists in the creation in the process of the specific quantity of short-circuit shots (as a rule 5-6) of the conditions. Maximally approximating the fact 6 short-circuits can occur with the transformer during the period of its operation as a result of possible emergencies.

Into the complex of short-circuit testing enters the inspection of the state of the most important elements of transformer, in particular windings. Already final conclusion about the results of tests was doing after the dismantling of transformer at the manufacturing plant.

The most well known Shortcurrent Testing Laboratories are KEMA (the Netherlands) (fig.2), CESI (Italy) (fig.3), EDF (France), Bina (India) (fig. 4), Xihari (China) and other.

FIG. 2 KEMA HIGH-POWER TESTING LABORATORY (THE NETHERLANDS)

FIG. 3 CESI POWER TESTING LABORATORY AT RONDISSONE (ITALY)

FIG. 4 1200 KV NATIONAL TEST STATION AT BINA (INDIA)

For substation electrical equipment of joint stock company "Federal Grid Company of Unified Energy System" (JSC "FGC UES") the problem of short-circuit withstand of power transformer's windings also is sufficiently urgent.

Short-circuit Transformer Testing is an Instrument for Reliability Improvement of Power Transformer Design

During short-circuit, the copper wires of transformer winding were deformed under the influence of electromagnetic forces by Biot-Savart's law, which will be in differential form [10-15]:

$$df = [B \cdot j]dv, \tag{1}$$

where: df – force's vector, which is influenced on the element of current with volume dv in magnetic field with magnetic induction B and current density j.

The vector product in the right part of equality showed that electromagnetic force is perpendicular to the direction of magnetic induction and current density (by left-hand rule).

The force, which acts on the winding or its part, can be calculated by integrating the equation (1):

$$F = \int_V [B \cdot j]\, dV \tag{2}$$

If B and j are perpendicular to each other and they are constant throughout entire volume, then electromagnetic force, which has influence on the element of current in magnetic field, is:

$$F = B \cdot l \cdot i, \tag{3}$$

where l–length of wire or winding; i–value of current into wire or winding; B–value of magnetic induction.

In the case of the appearance of short circuit regime as a result of the internal damage of transformer windings in service or during electrodynamic testing for short-circuit withstand with the artificial short-circuiting of the outlets of windings, the value of the greatest steady short-circuit current on high-voltage side in the double winding regime without taking into account the intermediate network elements will

comprise:

$$I_{SC\,HV} = \frac{U_{nom.tr}}{\sqrt{3}(Z_{S-C\_tr.} + Z_S + Z_L)}, \quad (4)$$

where: $U_{nom.tr}$ - nominal voltage of transformer's tap-changer; Z_L - the impedance of transmission line from the source of generation to Shortcurrent Testing Laboratory, then short-circuit impedance of transformer comprises (U in kV, S in MVA):

$$Z_{S-C\_tr.} = \frac{u_{S-C}(\%) \times U^2_{nom.tr}}{100 \times S_{nom.tr}} \quad (5)$$

where: $u_{S-C}(\%)$ -short-circuit voltage of transformer (from formular of transformer); $S_{nom.tr}$ -nominal capacity of transformer, then short-circuit impedance of network will be:

$$Z_S = \frac{U^2_{S\_nom.}}{S_{S-C\_S}} \quad (6)$$

where: $U_{S\_nom.}$ -nominal voltage of network; S_{S-C_S} - short-circuit capacity of system, which is determined by the network capacity.

Transformation ratio is equal to:

$$K_T = \frac{W_{HV}}{W_{LV}} \quad (7)$$

where: W_{HV} -the number of turns of HV winding; W_{LV} - the number of turns of LV winding.

The steady current in LV winding will comprise:

$$I_{SC\,LV} = I_{SC\,HV} \times K_T \quad (8)$$

Normalized values of first peak of aperiodic components (transient) short-circuit currents will comprise:

$$I_{ap.\,HV} = \sqrt{2} K_{ap.} I_{SC\,HV} \quad (9)$$

$$I_{ap.\,LV} = \sqrt{2} K_{ap.} I_{SC\,LV} \quad (10)$$

where: $K_{ap.}$ - the value of the impact coefficient (aperiodic coefficient) of short-circuit current, for the powerful transformers starts $K_{ap.}$ = 1,85.

The problem of the damage of power transformers from the loss short-circuit withstand is not always connected with the fact that they were originally connected dynamically unstable to short-circuit currents.

One should also consider that the actual short-circuit current could be more than permission according to the technical specifications, the effort of the pressing of windings was reduced or it was weakened by prior short-circuit, and other reasons.

The following aspects of the possibility of conducting the electrodynamic tests of the power transformers at new Shortcurrent Testing Laboratory in Russia should be taken into consideration:

1. proximity to the source of generation with a sufficient amount of short-circuit capacity (Ssc);
2. the agreement between generating companies, JSC "FGC UES" and system operator about the cooperation;
3. the proximity of manufacturing plants to Power Testing Laboratory;
4. suitable territory and infrastructure, including the railway for the transportation of transformers;
5. human factor, i.e., the presence of the qualified personnel;
6. large amount of financial investments.

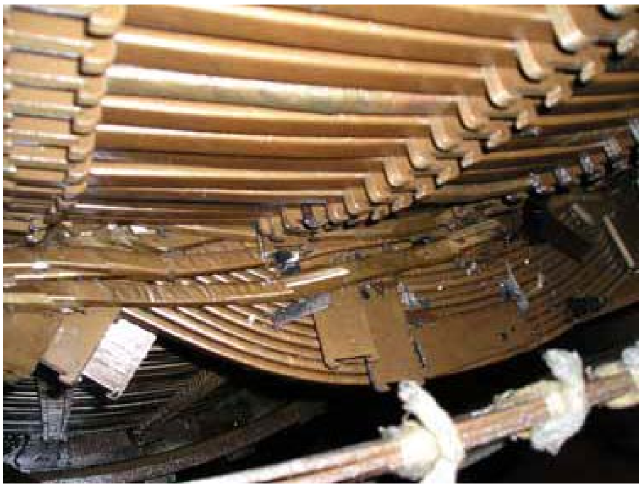


FIG. 5 RADIAL BUCKLING IN THE HV WINDING OF 250 MVA 500/110 KV AUTOTRANSFORMER

The damage of regulating winding was detected at the short-circuit tests of link 167MVA/ 500kV/ 220kV and 125MVA/ 220kV/ 110kV autotransformer at Togliatty Power Testing Laboratory, Russia. The regulating winding was untwisted at short-circuit tests of 25 MVA railway transformer. The windings of 160 MVA metallurgical transformer were pressed off during these testings. Deformations of turns were detected at the electrodynamic testing of 666 MVA 500 kV powerfull transformer for the Hydroelectric Power Station. The LVI method is very sensitive to small local changes of winding geometry: turn-to-turn and coil-to-coil capacitances, mutual inductances between transformer windings. The LVI oscillograms, containing basic resonance frequencies of transformer winding, are a "fingerprint" or condition state of transformer. Generally, windings of large power transformers have three basic resonance frequecies. Frequency Response

Analysis (FRA) showed presence of 110 kHz, 320kHz and 550kHz frequencies for 250MVA/220kV transformer. Radial buckling in the HV winding of 250 MVA /500/110 kV autotransformer after short-circuit in service is in the fig. 5.

The block diagram of new Shortcurrent Testing Laboratory (STL) planned for the building instead of Togliatty Power Testing Laboratory can include the following subdivisions:

- group of the calculation of short-circuit regimes;
- group of testings and diagnostics of the state of transformers before, after tests and between the short-circuit shots;
- group of servicing the high-voltage thyristor valves, which will be used in the regime of thyristor key;
- group of the maintenance intermediate transformer groups.

The electrical circuit of electrodynamic testing for short-circuit withstand of 250MVA/220kV power transformer is represented on the fig. 6, consists of disconnectors, circuit breakers, intermediate transformer groups, high-voltage thyristor valves, capacitive voltage dividers, limiting resistance, tested transformer at short-circuit and low-induction current-measuring shunts.

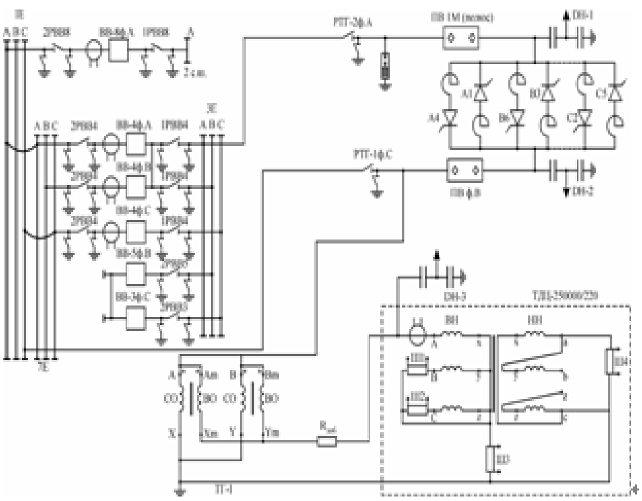


FIG. 6 THE ELECTRICAL CIRCUIT OF ELECTRODYNAMIC TESTING FOR SHORT-CIRCUIT WITHSTAND OF 250 MVA/220 KV POWER TRANSFORMER AT TOGLIATTY POWER TESTING LABORATORY, WHERE: 1PBB, 2PBB – DISCONNECTORS; BB – CIRCUIT BREAKERS; TT-1 - INTERMEDIATE TRANSFORMER GROUPS; A1-A4, B3-B6, C2-C5 - HIGH-VOLTAGE THYRISTOR VALVES; DH-1, DH-3 – CAPACITIVE VOLTAGE DIVIDERS; R - LIMITING RESISTANCE; TDC-250000/220 - . TESTED TRANSFORMER AT SHORT-CIRCUIT; Ш1-Ш4 – THE LOW-INDUCTION CURRENT-MEASURING SHUNTS

Short-circuit current oscillograms of HV and LV windings of 250 MVA /220 kV transformer during first short-circuit shot are in the fig. 7.

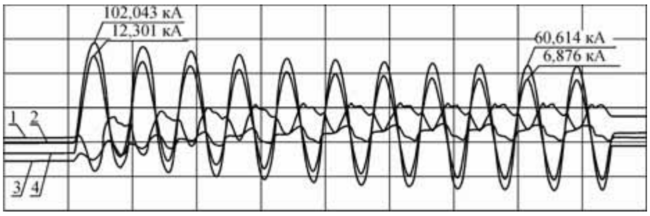


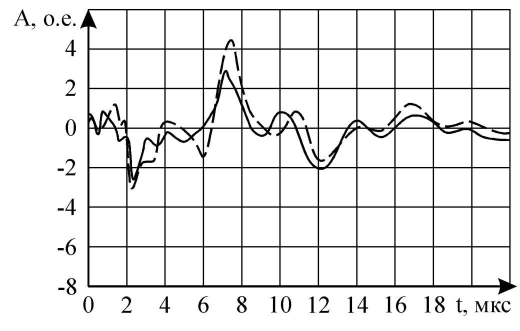
FIG. 7 SHORT-CIRCUIT CURRENT OSCILLOGRAMS OF HV AND LV WINDINGS OF 250 MVA /220 KV TRANSFORMER DURING FIRST SHORT-CIRCUIT SHOT OF PHASE «B», WHERE: 1- HV PHASE «A»; 2- LV PHASE «B»; 3- HV PHASE «C»; 4- HV PHASE «B»

The first variant of new Shortcurrent Testing Laboratory (STL) could become the power transformer testing for short-circuit withstand on the area of substation 750 kV Beliy Rast near Moscow, and with the use short-circuit capacity of Konakovskaya Electric Power Station with the length of 500 kV individual transmission line Konakovskaya- Beliy Rast of 88,9 kilometers (variant of 1).

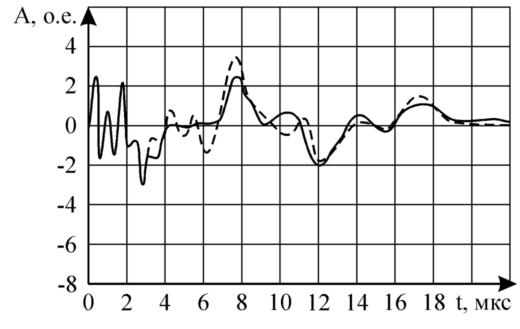
By the second alternative (variant of 2) it is possible to examine the electrodynamic testing of power transformers on the 750 kV Opitnaya substation near Tver, which is located near Konakovskaya Electric Power Station at a distance 430 meters only.

The third variant of new STL is on the 330 kV Vostochnaya substation near Saint-Petersburg.

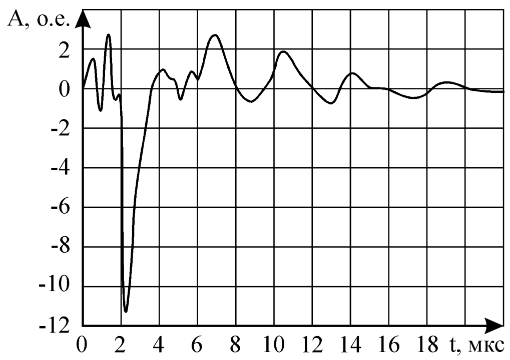
LVI-testing and FRA Method for Transformer Diagnostic



a) FOR LVI-TESTING OF PHASES «A-C» OF LV WINDING



b) FOR LVI-TESTING OF PHASES «A-B» OF LV WINDING



c) FOR LVI-TESTING OF PHASES «B-C» OF LV WINDING

FIG. 8 LVI-OSCILLOGRAMS OF IN LV WINDING OF 250 MVA/220 KV TRANSFORMER AFTER SHORT-CIRCUIT SHOT WITH 85% VALUE OF TRANSIENT (APERIODIC) CURRENT IN THE PHASE «A», ILLUSTRATING THE APPEARANCE OF SIGNIFICANT AMPLITUDE-FREQUENCY CHANGES WITH VALUE TO 1,5 VOLTS, SHORT-CIRCUIT IMPEDANCE ΔZK =+1% (RADIAL DEFORMATIONS)

Significant amplitude-frequency changes with value to 1,5 Volts in the LVI- oscillograms, corresponding to radial deformations in LV winding of phase A, were occurred during the short-circuit tests of phase A of 250 MVA/220 kV transformer after short-circuit shot with 85% value of transient (aperiodic) current . Conclusion was made about the impossibility of conducting further transformer testing (fig. 8).

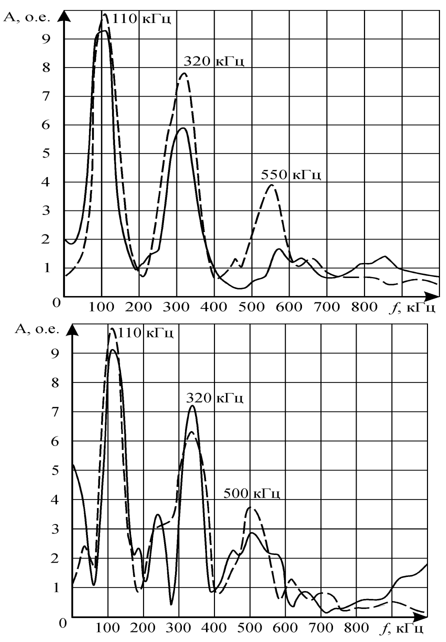


FIG. 9 CALCULATED FRA-SPECTRUM OF LV WINDING OF 250 MVA/220 KV TRANSFORMER AFTER SHORT-CIRCUIT SHOT WITH 85% VALUE OF TRANSIENT (APERIODIC) CURRENT IN THE PHASE «A», BUILT ON THE BASIS OF LVI-OSCILLOGRAMS

The changes in the spectra of windings, which occurred as a result of radial deformations, bear in essence amplitude nature, while changes in the frequency are less significant. One of the fundamental resonance frequencies (fig. 9) appears frequently in the period of 3 microseconds, i.e. 330 kHz.

It is confirmed by the calculations of spectra that the frequency of 320 kHz is one of the fundamental resonance frequencies. Resonances are also the frequencies of 110 kHz and 510 divided by 550 kHz. It is possible to establish an increase in the amplitudes after the appearance of the deformations of at frequencies 320 kHz and 550 kHz (fig. 9).

Typical example of deformation due to radial buckling in the A phase LV internal winding of 250 MVA/220kV transformer(Δ Xk= +1%, LVI-oscillograms is in the fig. 8, FRA-spectrum is in the fig. 9).

FIG. 10 TYPICAL EXAMPLE OF DEFORMATION DUE TO RADIAL BUCKLING IN THE «A» PHASE LV INTERNAL WINDING OF 250 MVA /220 KV TRANSFORMER

The preliminary conclusion, which can be made on the basis of the analysis of the results of FRA-spectrum of LV winding of the phase "A" of 250 MVA /220 kV transformer, consists in the fact that the radial deformations of windings correspond to an increase in the amplitude value of average and high frequencies 1,3 divided by 2 times. For large transformers in the spectra of their windings are three fundamental resonance frequencies (110, 320 and 500… 550 kHz). It is possible to establish that increase named above in the amplitudes of the second and third resonance frequency (average and high) is the diagnostic sign of radial deformations.

125 MVA/220 kV/110 kV autotransformer was switched off by gas relay protection after internal short-circuit at the "Kostroma-2" substation in service. The tank of autotransformer was not deformed (fig. 11). Serious deformations and turn-to-turn internal short-circuit were detected in MV 110 kV winding, regulating winding and LV winding by LVI-testing, short-circuit inductive reactance measurements and iron core losses methods. LVI oscillograms of MV 110 kV winding, including turns of regulating winding (a),

and oscillograms of LV winding (b) are in the fig. 12. The LVI amplitude-frequency differences of C phase from A and B phases are noticeable. The short-circuit impedance differences of C phase from A and B phases are Δ Xk= -11.6% in MV-LV winding regime, and Δ Xk= -7% in HV-LV winding regime.

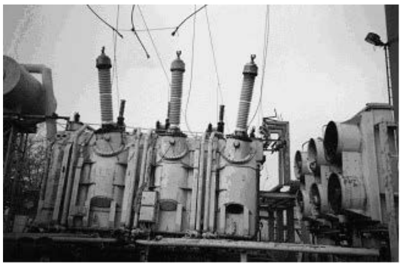
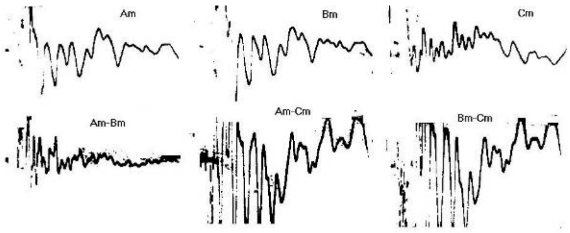
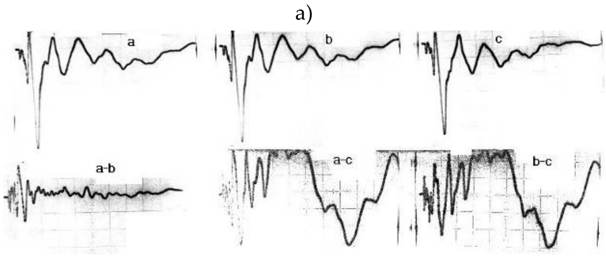


FIG. 11 125 MVA/220 KV/110 KV AUTOTRANSFORMER AFTER INTERNAL SHORT-CIRUIT AT «KOSTROMA-2» SUBSTATION



a)



b)

FIG. 12 LVI OSCILLOGRAMS OF MV 110 KV WINDING, INCLUDING TURNS OF REGULATING WINDING (a), AND OSCILLOGRAMS OF LV WINDING (b) OF 125 MVA/220 KV/110 KV AUTOTRANSFORMER AFTER INTERNAL SHORT-CIRAT AT «KOSTROMA-2» SUBSTATION, ILLUSTRATING AMPLITUDE-FREQUENCY DIFFERENCES OF «C» PHASE

The main goal of diagnostic investigation of 125MVA/ 220kV/110kV autotransformer was to define the possibility of repairing. Base on the results of this diagnostic investigation, the substitution of autotransformer was planed.

The block 80MVA 110kV transformer had serious amplitude frequency LVI LV1-LV2 winding oscillogram differences after generator side short-circuit at Heat Electric Power Station. The LV- winding FRA-spectrum of 80 MVA 110 kV transformer changed after short-circuit. The original 300kHz, 500kHz, 700kHz resonance frequencies disappeared and a new 400 kHz, 800kHz resonance frequencies appeared (Fig. 13, 14, 15). The LVI-tests and spectrum analysis of 80 MVA 110kV transformer's LV-windings detected axial electrodynamic deformations.

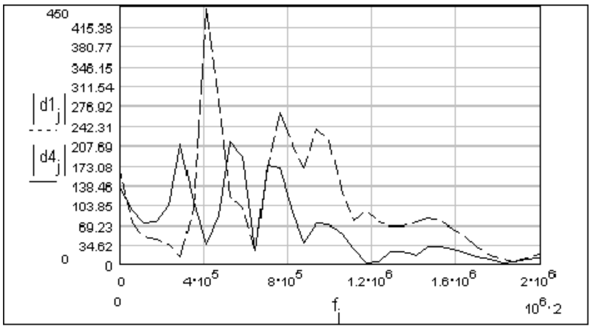


FIG. 13 SPECTRUMS OF "A-B" PHASES LVI SIGNAL OF LV WINDING OF THE BLOCK 80 MVA/110 KV TRANSFORMER BEFORE AND AFTER GENERATOR SIDE SHORT-CIRCUIT

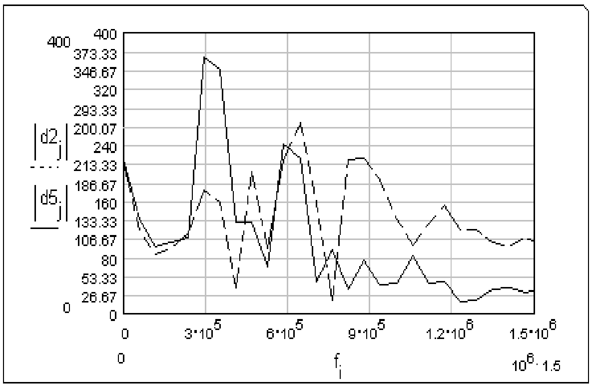


FIG. 14 SPECTRUMS OF "A-C" PHASES LVI SIGNAL OF LV WINDING OF THE BLOCK 80 MVA/110 KV TRANSFORMER BEFORE AND AFTER GENERATOR SIDE SHORT-CIRCUIT

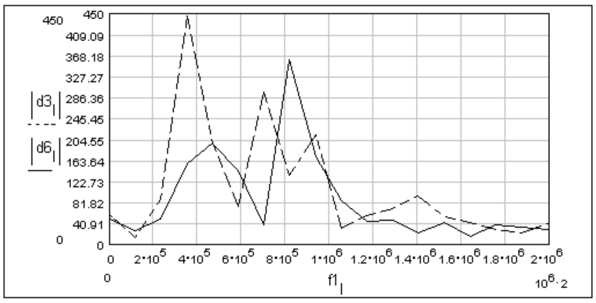


FIG. 15 SPECTRUMS OF "B-C" PHASES LVI SIGNAL OF LV WINDING OF THE BLOCK 80 MVA/110 KV TRANSFORMER BEFORE AND AFTER GENERATOR SIDE SHORT-CIRCUIT

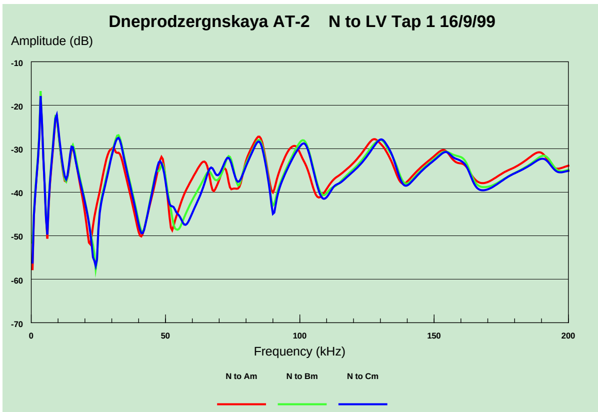


FIG 16 FRA RESPONSES OF POWER TRANSFORMER WITH HOOP BUCKLING OF AT-2 AUTOTRANSFORMER (ZTR, ZAPOROZHYE, UKRAINE) AFTER INTERNAL SHORT-CIRCUIT AT DNEPRODZERGNSKAY SUBSTATION

FRA responses of power transformer with hoop buckling at Dneprodzergnskay substation are in the fig. 16.

Conclusions

The most well known Shortcurrent Testing Laboratories are KEMA (the Netherlands), CESI (Italy), EDF (France), Bina (India), Xihari (China) and other.

Transformer testing for short-circuit withstand is an instrument for reliability improvement of power transformer design. All transformer design elements (winding, pressing system, and etc.) must be checked during short-circuit testing by real values of short-circuit currents.

Shortcurrent Testing Laboratory can include the following subdivisions: for calculation of short-circuit regimes; for testing and diagnostic the state of transformers; for service the high-voltage thyristor valves; for the maintenance intermediate transformer groups.

The electrical circuit of electrodynamic testing for short-circuit withstand of power transformer consists of disconnectors, circuit breakers, intermediate transformer groups, high-voltage thyristor valves, capacitive voltage dividers, limiting resistance, tested transformer at short-circuit and low-induction current-measuring shunts.

The low voltage impulse testing is a very sensitive and reliable method of deformation detection of transformer windings.

The LVI oscillograms are a "fingerprint" of transformer.

This winding fingerprints are defined by major resonance frequencies (a winding spectrum). The 250 MVA/220 kV winding transformer's FRA-spectrum contained 110 kHz, 320 kHz and 550 kHz frequencies which are changed 1.3-2 times after the mechanical radial winding deformations. The LV- winding FRA-spectrum of 80 MVA 110 kV transformer changed after short-circuit. The original 300 kHz, 500 kHz, 700 kHz resonance frequencies disappeared and new 400 kHz, 800 kHz resonance frequencies appeared in spectra.

ACKNOWLEDGMENT

Mr. Richard Malewski, Poland, Mr. Giorgio Bertagnolli, ABB Transformatori, Legnano (Milano), Italy, and Mr. John Lapworth, Great Britain, are greatly acknowledged for supporting this study. Cooperation of Universities and Innovation Development, Doctoral School project “Complex diagnostic modeling of technical parameters of power transformer-reactor electrical equipment condition” has made publishing of this article possible.

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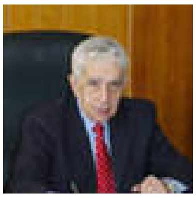

Yury G. Shakaryan was born in 1933, Russia, PhD of El. Eng., CIGRE member, professor, the academician of the Academy of electrotechnical Sciences of Russia, the member of the American institute of engineers, electrical engineers and electronics specialists. Deputy of general director, scientific leader of Scientific and Technical Center of Federal Grid Company of United Energy System, Russia.

Renowned scientist in the field of electric power systems, electrical machines, electromechanical complexes, automated electric drive. He is the author of approximately 320 scientific works, 11 books, 88 inventions and patents.

He is founder of the new scientific direction, connected with the development, by creation and introduction of the electrical machine thyristor valve complexes, which have been the intellectual systems, consisting of the electrical machines and the controlled frequency converters.

Basic researches executed under its scientific management and on their basis are for the first time in the world practice developed, created and inculcated the electrical machines of new type – asynchronized.

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